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First year performance report for the grant:

HEALTH MONITORING OF COMPOSITE MATERIAL STRUCTURES USING A VIBROMETRY TECHNIQUE

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by

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1. INTRODUCTION

Large composite material structures such as aircraft and Reusable Launch Vehicles (RLVs) operate in severe environments comprised of vehicle dynamic loads, aerodynamic loads, engine vibration, foreign object impact, lightning strikes, corrosion, and moisture absorption. These structures are susceptible to damage such as delamination, fiber breaking/pullout, matrix cracking, and hygrothermal strain. To ensure human safety and load-bearing integrity, these structures must be inspected to detect and locate often invisible damage and faults before becoming catastrophic. Moreover, nearly all future structures will need some type of in-service inspection technique to increase their useful life and reduce maintenance and overall costs.

Possible techniques for monitoring the health and indicating damage on composite structures include; c-scan, thermography, acoustic emissions using piezoceramic actuators or fiber-optic wires with gratings, laser ultrasound, shearography, holography, x-ray, and others. These techniques have limitations in detecting damage that is beneath the surface of the structure, far away from a sensor location, or during operation of the vehicle. The objective of this project is to develop a more global method for damage detection that is based on structural dynamics principles, and can inspect for damage when the structure is subjected to vibratory loads to expose faults that may not be evident by static inspection. A Transmittance Function Monitoring (TFM) method is being developed in this project for ground-based inspection and operational health monitoring of large composite structures such as the RLV shown in Fig. 1. A comparison of the features of existing health monitoring approaches [1-3] and the proposed TFM method is given in Table 1. The information in Table 1 will be updated as the techniques are studied further, and is useful for evaluating advantages of the new method(s) developed in this project. Progress made in the first year period of this three year project to develop a vibrometry technique for health monitoring of composite structures is presented in this report.

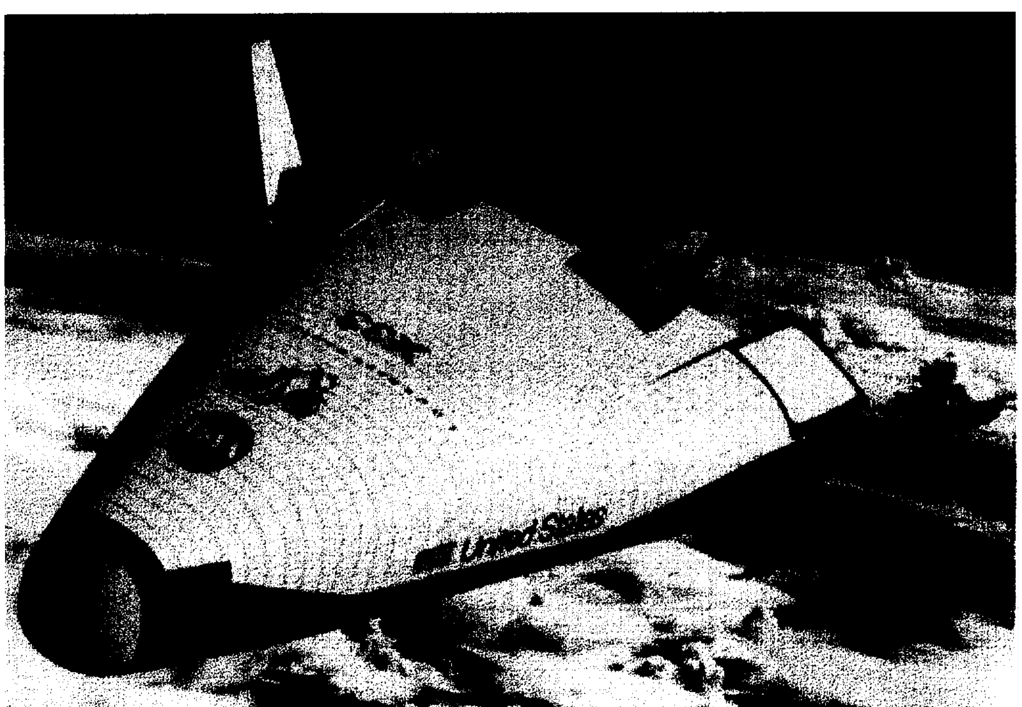

Figure 1. Reusable launch vehicle application for health monitoring

Table 1. Comparison of health monitoring techniques

TECHNIQUE	INITIAL DAMAGE	AFFECTED BY ENVIRONMENT	NON-OPERATIONAL	OPERATIONAL	GLOBAL DAMAGE	INTERIOR DAMAGE	NON-CONTACT	IN-OUT MODEL	FEM MODEL	HISTORICAL DATA
Acoustic Emissions	Y	N	N	Y	N	Y	N	N	N	N
Laser Holography	Y	N	Y	N	Y	N	Y	N	N	N
Impedance/PZT	Y	Y	Y	Y	N	Y	N	Y	N	Y
Modal Methods	N	Y	Y	Y	Y	Y	Y	N	Y	N
Transmittance Funct.	N	Y	Y	Y	Y	Y	Y	Y	N	Y
Shearography	Y	N	Y	N	Y	N	Y	N	N	N
Fiber -optic AE	Y	N	N	Y	N	Y	N	N	N	N
Fiber-optic strain	Y	N	Y	Y	N	Y	N	N	N	N
Freq. Resp. Ref. Fun.	N	Y	Y	Y	Y	Y	Y	Y	N	Y
C-scan	Y	N	Y	N	N	N	N	N	N	N
X-ray	Y	N	Y	N	N	Y	N	N	N	N
Thermography	N	N	Y	N	Y	N	Y	N	N	N

2. DAMAGE DETECTION THEORY

The Transmittance Function (TF) method [4,5] and an extension to compute curvatures is developed with reference to the schematic of the Transmittance Function Monitoring (TFM) system given in Figure 2.

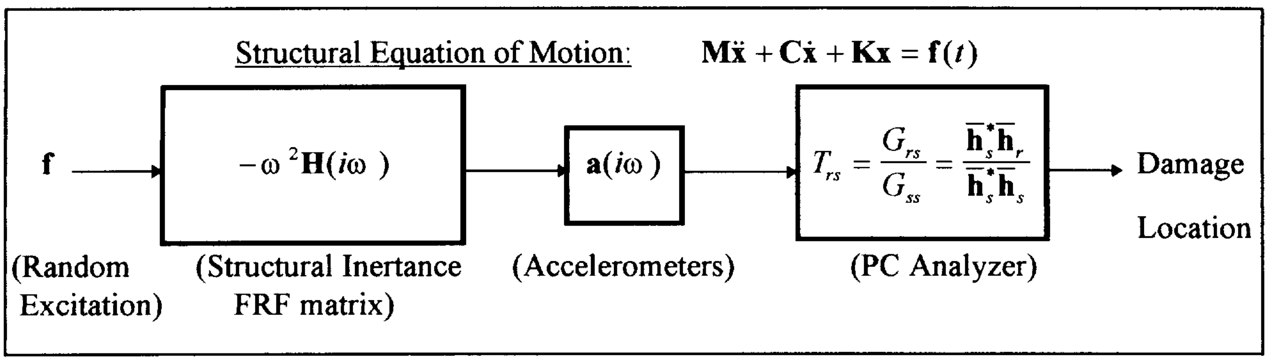

Figure 2. Schematic of the Transmittance Function Monitoring system

The excitation is from random uncorrelated forces with the same mean-square magnitude, or an impact hammer. Computing the finite Fourier Transform of the structural acceleration vector gives:

$$\mathbf{a}(\omega, T_o) = -\omega^2\mathbf{H}(\omega)\mathbf{f}\ (\omega, T_o) \tag{1}$$

where $\mathbf{H} = (\mathbf{K} - \omega^2\mathbf{M} + i\omega\mathbf{C})^{-1}$, and $\mathbf{f}$ is the loading vector. Multiplying (1) by the complex conjugate transpose (*) of $\mathbf{a}$ gives:

$$\mathbf{aa}^* = \omega^4\mathbf{H(f)(f)}^*\mathbf{H}^* \tag{2}$$

Taking the expectation of both sides of (2) over a "long period" T_o, yields:

$$\mathbf{G}_{aa} = \omega^4\mathbf{HG}_{ff}\mathbf{H}^* \tag{3}$$

The spectral densities are:

$$G_{rs}(i\omega) = \frac{Lim}{(T_o \to \infty)}\frac{2}{T_o}E[a_r^* a_s] \qquad \mathbf{G}(i\omega) = \frac{Lim}{(T_o \to \infty)}\frac{2}{T_o}E[\mathbf{ff}^*]\ . \tag{4}$$

With this excitation $\mathbf{G}_{ff}$ is a diagonal matrix of mean square forces. Let $\mathbf{h}$ be a column of $\mathbf{H}$. By examining the scalar entries of $\mathbf{G}_{aa}$ and dividing by the autospectra, we obtain:

$$\frac{G_{rs}}{G_{ss}}\mathbf{h}_s^*\mathbf{G}_{ff}\mathbf{h}_s = \mathbf{h}_r^*\mathbf{G}_{ff}\mathbf{h}_s \tag{5}$$

A requirement is that all random forces must have the same mean-square magnitude or be zero in the frequency range where we are looking for damage. This gives the transmittance function:

$$T_{rs} = \frac{G_{rs}}{G_{ss}} = \frac{\overline{\mathbf{h}}_r^*\overline{\mathbf{h}}_s}{\overline{\mathbf{h}}_s^*\overline{\mathbf{h}}_s}. \tag{6}$$

where $\overline{\mathbf{h}}_r^*$ is the reduced size vector corresponding to the Degrees-of-Freedom (DOF) where the excitations are applied. The TFs are a non-dimensional complex quantity that define how vibration (amplitude and phase) is transmitted between DOFs r and s on the structure versus frequency. The TFs are also functions of the columns of the FRF matrix, and thus a change in the TFs represents a change in the structural properties due to damage. The TF matrix is written as (n is the number of accelerometers on the structure):

$$\mathbf{T}=\begin{bmatrix} 1 & T_{12} & \cdots & T_{1n} \\ T_{21} & 1 & & T_{2n} \\ \vdots & & \ddots & \vdots \\ T_{n1} & T_{n2} & \cdots & 1 \end{bmatrix} \tag{7}$$

Either the first row or first upper diagonal of the $\mathbf{T}$ matrix is used to detect damage. Damage is determined using a normalized damage matrix defined as:

$$\mathbf{D} = \int_{f1}^{f2} |\mathbf{T}^h - \mathbf{T}^d| / |\mathbf{T}^h| \, df \tag{8}$$

For symmetric structures, it is possible to detect damage without using historical data by monitoring TFs that approximately equal one in the undamaged condition.

2.1 Rotational Transmittance Functions

Rotations are computed from translational measurements using finite-differences because only translations are practical to measure using accelerometers or a laser. Using PZT patches to get strains and rotations/curvatures is another possible approach. The rotation at a point on a structure for small deflections is computed as:

$$\theta_i = \frac{\partial y_i}{\partial x_i} \approx \frac{y_{i+1} - y_{i-1}}{2l} \tag{9}$$

Rotational Transmittance Functions are computed between rotational DOFs (r,s) using:

$$T_{rs} = \frac{G_{rs}}{G_{ss}} = \frac{\mathbf{h}_s^*\mathbf{h}_r}{\mathbf{h}_s^*\mathbf{h}_s} \tag{10}$$

2.2 Curvature Transmittance Functions

Curvatures are computed from translational measurements using finite-differences. The one-dimensional curvature at a point on a structure for small deflections is:

$$\rho_i = \frac{\partial^2 y_i}{\partial x_i^2} \approx \frac{y_{i+1} - 2y_i + y_{i-1}}{l^2} \tag{11}$$

The curvature transmittance function is derived starting with the curvature as:

$$\rho = \mathbf{T}_c\mathbf{x} \tag{12}$$

where $\mathbf{x} = \mathbf{Hf}$ and $\mathbf{T}_c$ is the curvature transformation matrix. The curvature cross-spectral density matrix is derived as:

$$\mathbf{G}_{\rho\rho} = E(\rho\rho^*) = \mathbf{T}_c \mathbf{G}_{xx} \mathbf{T}_c^* = \mathbf{H}_c \mathbf{H}_c^* |f_o|^2 \tag{13}$$

where $\mathbf{H}_c = \mathbf{T}_c \mathbf{H}$ is the curvature FRF matrix. The curvature transmittance function is then:

$$T_{rs}^c = \frac{(\mathbf{h}^c)_s^* (\mathbf{h}^c)_r}{(\mathbf{h}^c)_s^* (\mathbf{h}^c)_s} \tag{14}$$

where the $\mathbf{h}^c$ are the columns of the curvature FRF matrix. An elemental average curvature can also be defined using the curvature computed as:

$$\rho_i = \frac{\theta_{i+1} - \theta_i}{l} \quad . \tag{15}$$

2.3 Computing Cross-spectral Densities

The full cross-spectral density matrix can be generated using one reference point and one input for structures that have symmetric matrices. The technique can also be extended for use with structures that have skew-symmetric matrices due to gyroscopic forces, such as helicopter rotors operating at a constant speed. The displacement vector in the frequency domain is:

$$\mathbf{x} = \mathbf{Hf} \tag{16}$$

where $\mathbf{f} = f_o \begin{bmatrix} 0 & 0 & \cdots & 1 & 0 & \cdots & 0 \end{bmatrix}^T$ and only the k*th* entry is non-zero. The displacement equation becomes:

$$\mathbf{x} = \mathbf{h}_k f_o \tag{17}$$

where $\mathbf{h}_k$ is the kth column of $\mathbf{H}$. The cross-spectral density matrix of the displacements is:

$$\mathbf{G}_{xx} = \mathbf{h}_k \mathbf{h}_k^* |f_o|^2 \tag{18}$$

or

$$\begin{bmatrix} G_{11} & G_{12} & & G_{1,n} \\ G_{21} & G_{22} & & G_{2,n} \\ & & G_{33} & \\ & & & \\ G_{n,1} & & & G_{n,n} \end{bmatrix} = |f_o|^2 \begin{bmatrix} h_1 h_1^* & h_1 h_2^* & & h_1 h_n^* \\ h_2 h_1^* & h_2 h_2^* & & h_2 h_n^* \\ & & h_3 h_3^* & \\ & & & \\ h_n h_1^* & h_n h_2^* & & h_n h_n^* \end{bmatrix} \tag{19}$$

From measurements, all auto-spectral densities and one row of the G matrix are known:

$$G_{1,p} G_{2,p} G_{3,p} \cdots G_{n,p} G_{11} G_{22} \cdots G_{nn} .$$

By symmetry, $G_{i,j} = G_{j,i}^*$. For a force only at DOF p, the full G matrix can be written as:

$$G_{i,j} = h_i h_j^* |f_o|^2 = \frac{(h_p h_j^*)(h_i h_p^*)}{|h_p|^2} |f_o|^2 = \frac{G_{pj} G_{ip}}{G_{pp}} . \tag{20}$$

This approach can reduce memory requirements in analyzers and construct the full spectral density matrix using sequential measurements from a scanning laser doppler vibrometer. Possible characteristics of the Transmittance Function Monitoring (TFM) method are:

1) No structural model is needed.
2) Excitation does not need to be measured.
3) Damage can be detected using uniform random ambient vibration.
4) TFs are sensitive because of the ratio of peaks and valleys and can detect small damage.
5) The TFM method is repeatable because environmentally induced changes are mostly canceled by taking ratios of responses, and by frequency shifting.
6) Large structures can be inspected using a SLDV.
7) TFs have a high dynamic range and can decompose the response signal/noise into different frequency bands to focus on abrupt spectral changes due to damage.
8) Potentially no historical data needs to be stored for dense spatial measurements.
9) Measurement noise tends to be canceled by normalization in the TF.
10) Damage may be detected using symmetry of the structure and loading without storing historical data.
11) The proposed technique uses wide band random excitation to expose faults that may not be obvious when using static inspection methods such as holography, thermography, visual inspection, and other techniques.

3. SIMULATION

The Transmittance Function (TF) algorithm has been programmed using the MATLAB code and a finite element model of a beam is being used to develop and test the damage detection algorithm. The 30 DOF model of the beam is shown in Figure 3. A beam is used for the simulation because the finite-element-model is easy to create and runs quickly using the damage detection algorithms.

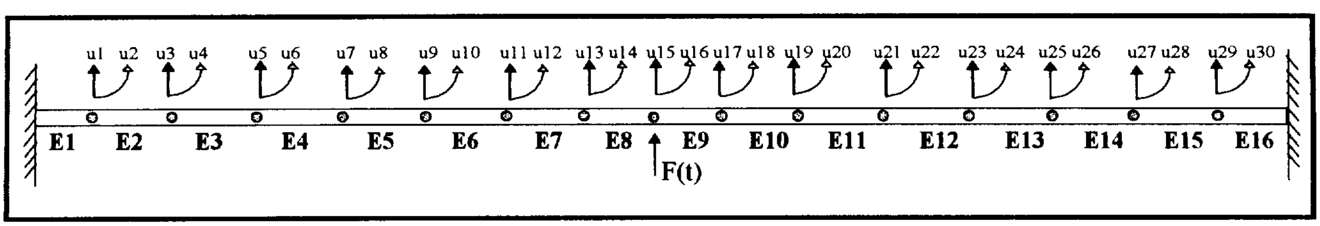

Figure 3. Fixed-fixed beam model for simulation

The example shown here models damage to the beam as a 25% reduction in stiffness at element 4, and curvature TFs are used to detect damage. The TFs and damage indicator for the 30 DOF beam model are shown in Figure 4. The peak D value indicates that damage is approximately located at TFs 2 and 3 which correspond to damage in elements 3 or 4. This is also obvious by comparing the TF plots which have the largest difference near the damage, i.e. T23 and T34. The finite-difference approximation tends to spread out the damage location, and using closer spaced measurements would make the damage location more exact. This simulation shows that with the curvature TFs it is possible to detect damage, and also to locate damage if close measurements are taken.

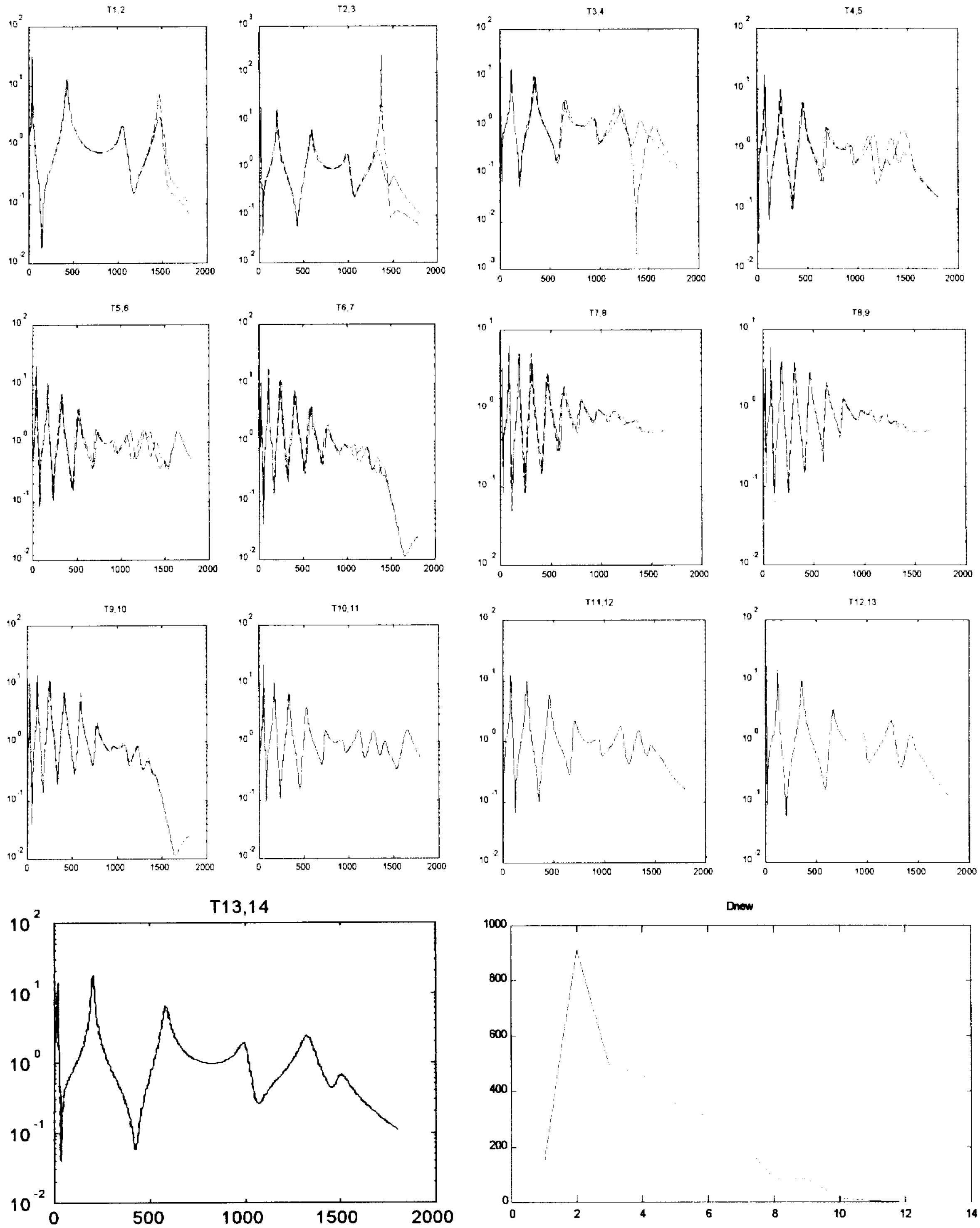

Figure 4. TFs and the damage indicator for damage in beam element 4
(Healthy structure response is red, damaged is blue (dashed))

The analytical studies performed show that the TFM algorithm is very sensitive and can detect small damage, but locating damage using translational DOFs and a small number of sensors is difficult. A different algorithm that uses Frequency Response Reference Functions (FRRFs) from the pre-damage structure to detect damage was developed to more accurately located damage. This algorithm [6] can accurately locate damage and has shown that rotations and curvatures are more sensitive to damage than translations. However, the FRRF algorithm would be difficult to apply to large structures because of the requirement to measure the Frequency Response Function (FRF) matrix for the number of sensors on the structure. At this stage, the TF curvature algorithm is being improved by developing a more sensitive damage indicator, and curvatures are being tested to detect damage with/without using historical data.

4. EXPERIMENTATION

The original proposal specified damage detection testing on a number of different types of flat composite panels. The reviewers of the proposal suggested testing a smaller number of large panels to more closely represent the actual dynamic characteristics of large structures, and the technical monitor suggested testing a curved panel. These suggestions are being followed and three test articles and fixtures have been built. These are: a table fixture in which two 48 inch by 48 inch by ¼ inch G-10 fiberglass epoxy panels were screwed together to simulate reversible delamination damage; a vertical frame with the capability to pre-stress a 48 inch by 48 inch by ¼ inch panel to a curved shape; and a 48 inch by 3 inch by ¼ inch cantilever beam test fixture.

4.1 Delamination Detection

This experiment uses two fiberglass panels with dimensions 48 inches by 48 inches by ¼ inch. Steel bolts that are ¼ inch diameter are used to hold the panels together (144 inside bolts and 52 boundary bolts) thus creating one panel that is ½ inch thick that is the horizontal top of a table, as shown in Figure 5. Screws can be loosened to simulate different sizes and locations of reversible delamination damage. The panel is bolted along all edges to a horizontal steel frame to simulate fixed BC's. Four piezoceramic accelerometers are attached to the panel. An impact hammer or piezoceramic inertial actuator is used to excite the plate in the center. Signal processing is done using four channels of a 16-channel DP-420 FFT analyzer board inside a PC. The experiment is performed first for the undamaged panel and the data is then saved as the "healthy" transmittance functions. Two separate experiments were run with no damage to show repeatability of the data. The damage indicator value D_{max} for the healthy-healthy case (i.e. the error or noise level) is 0.12. Next, one bolt 7 inches from the panel center is loosened to simulate delamination and the maximum value of the damage matrix D for the healthy-damage1 case is 0.46. Finally four bolts are loosened and the maximum value of the damage indicator matrix D for the healthy-damage4 case is 0.82. The TF plots for the healthy-healthy case, and the healthy-damage4 case are shown in Figures 6 and 7, respectively. In this example the simulated delamination damage due to loosening one and then four screws was detected. With only four accelerometers the damage could not be located. This experiment of loosening 1 and then 4 out of 144 bolts successfully detected a minor (~1-3% area) delamination in the composite material panel. The testing was repeated using an impact hammer for excitation at the center, for different combinations of loosened screws. Results for all the different cases of delamination damage are given in Table 2.

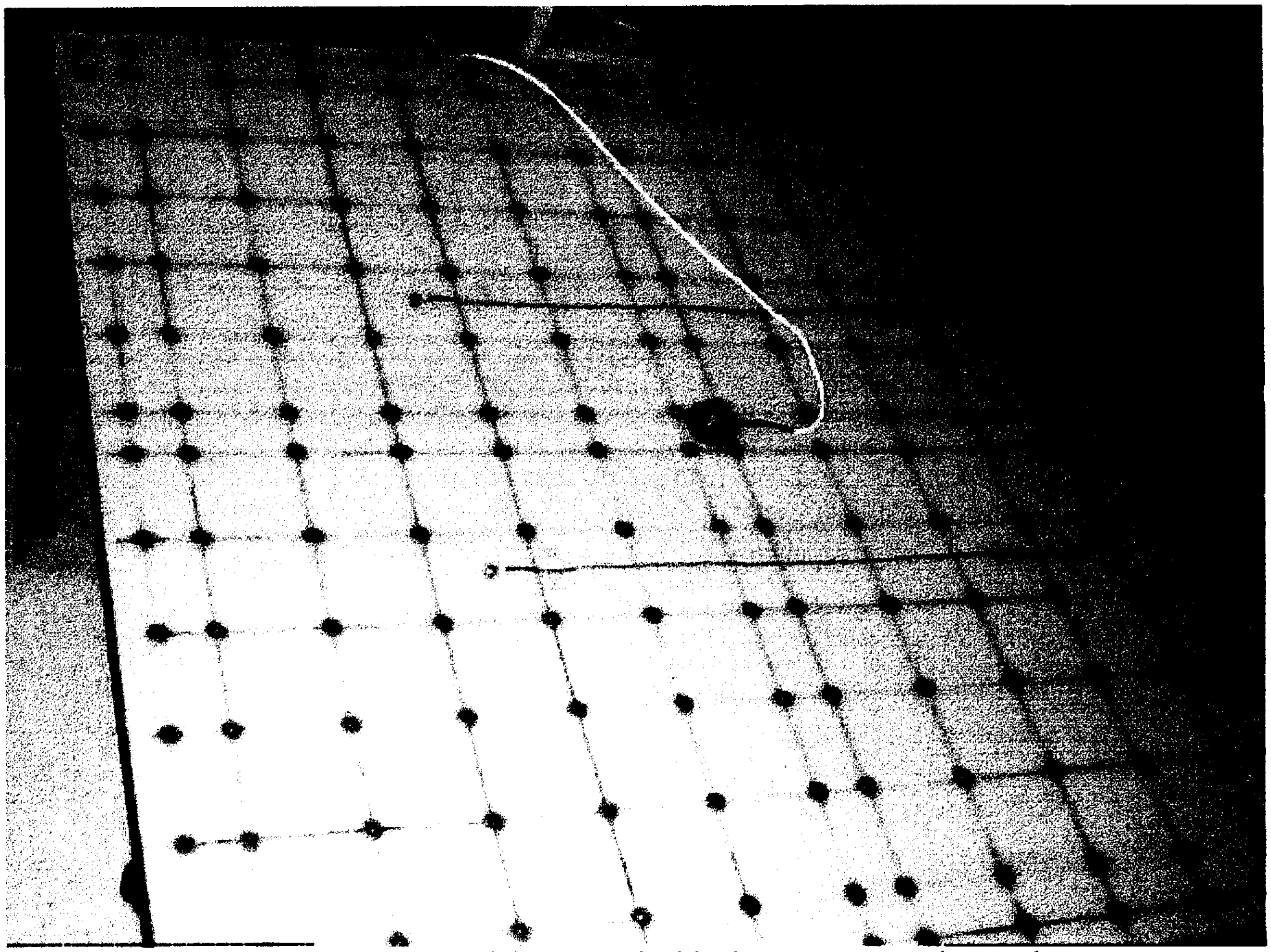

Figure 5. Composite material test panel with piezo-actuator and 4 accels.

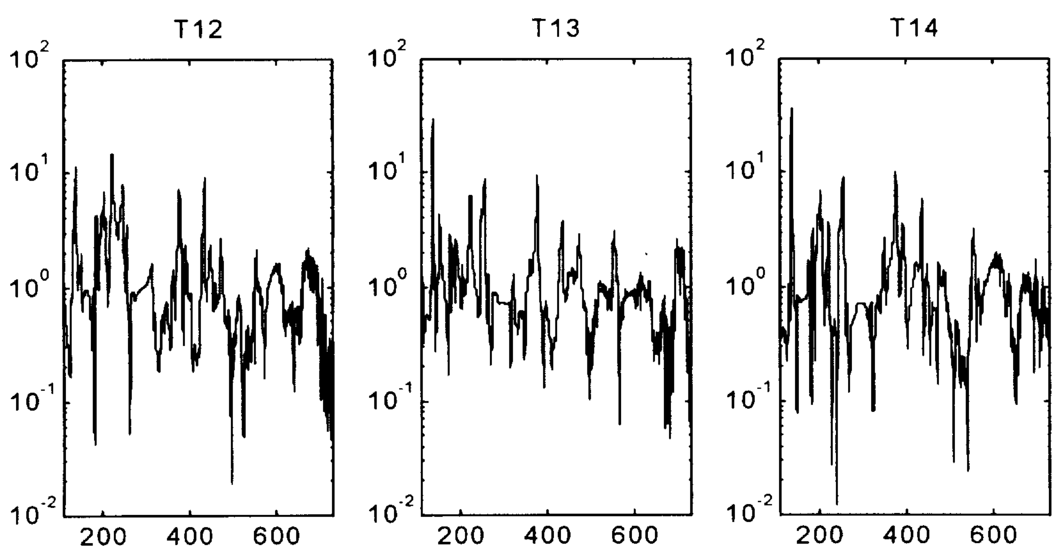

Figure 6. Three TFs for healthy1 and healthy2 delamination case (blue=healthy1, red=healthy2)

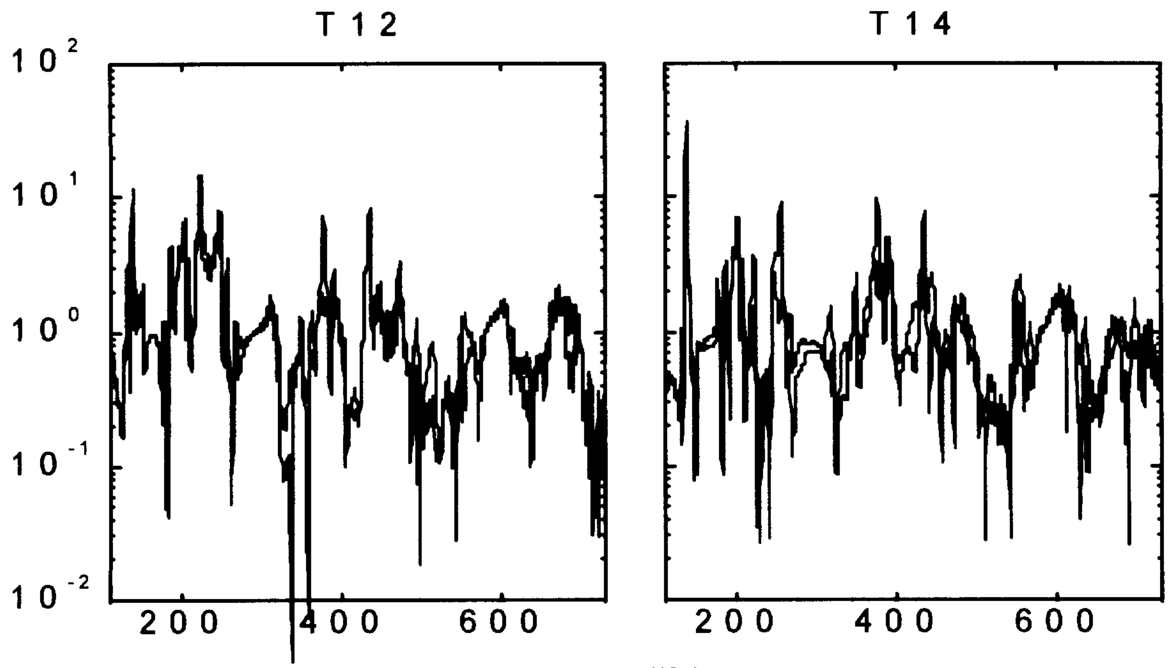

Figure 7. Two TFs for healthy1 and damage4 delamination case (blue=healthy, red=damaged)

Table 2. Summary of damage detection results for delamination damage

DAMAGE	**DAMAGE INDICATOR VALUE**
	(Piezo-excitation, 30 avgs)
None	0.12
1-bolt loose:	0.46
4- bolts loose:	0.82
	(Hammer excitation, 20 avgs)
None	0.2259
1-bolt loose: no. 89	0.3010
3-bolts loose: nos. 88,89,101	0.4540
6-bolts loose: nos. 88,89,90,100,101,102	0.7317
10-bolts loose: nos. 68,69,81,88,89,90,100,101,102	0.7840

In this example damage was detected using the piezo and hammer excitation, but the repeatability needs to be improved by using more frequency lines and more averages.

4.2 Damage Detection on a Curved Panel

A curved fiberglass panel 1/4 in by 48 inch by 48 inch is used with four accelerometers to detect damage, and is shown in Figure 8. Damage is simulated as: (a) an added mass (100 g); and (b) a 2 inch saw cut at the top of the panel. White noise random vibration input from 100-800 Hz is used to excite the panel. A piezo-ceramic inertial actuator is placed at the center of the panel to provide the excitation. The damage calculation is carried out over the 152-780 Hz range, and twenty averages of data are taken. Sample data from the healthy-healthy case is shown in Fig. 9, and the healthy-damaged case in Figure 10. The results of this testing are listed in Table 3.

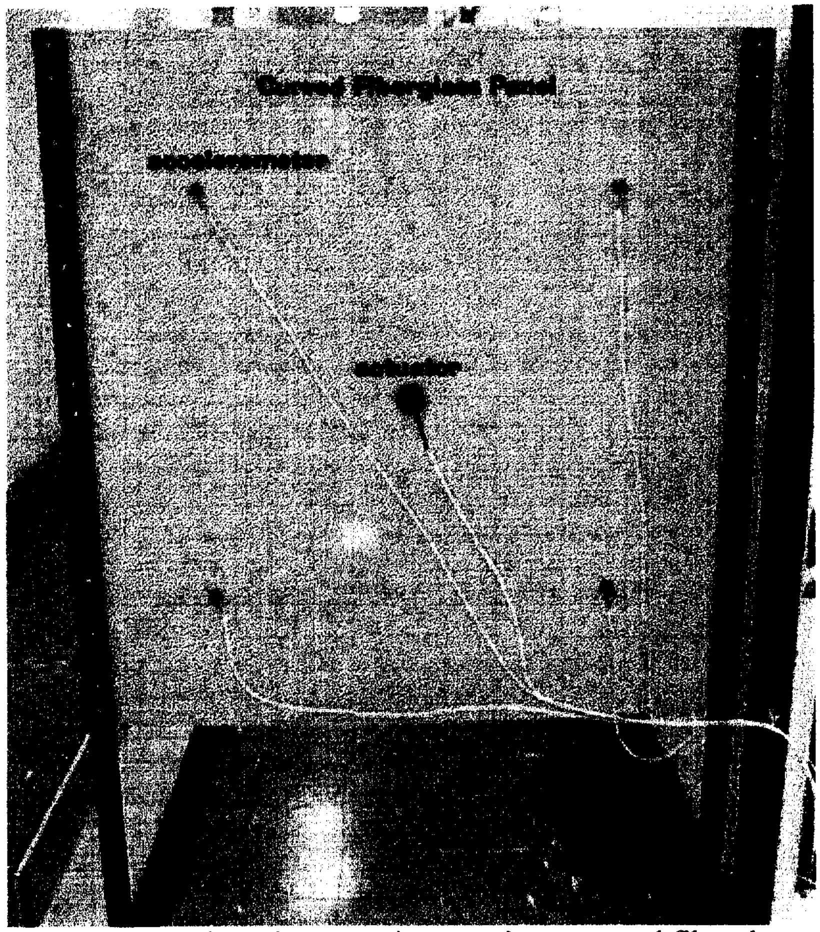

Figure 8. Damage detection experiment using a curved fiberglass panel

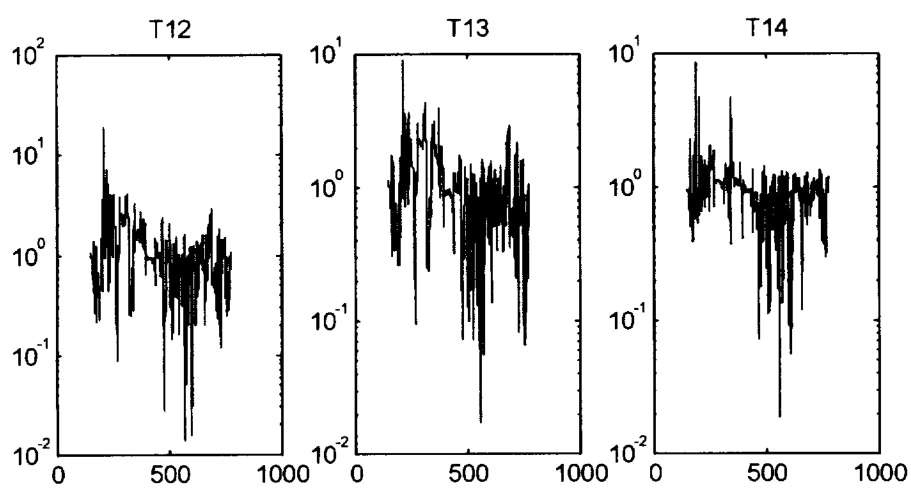

Figure 9. Three TFs for healthy1 and healthy2 case for curved panel

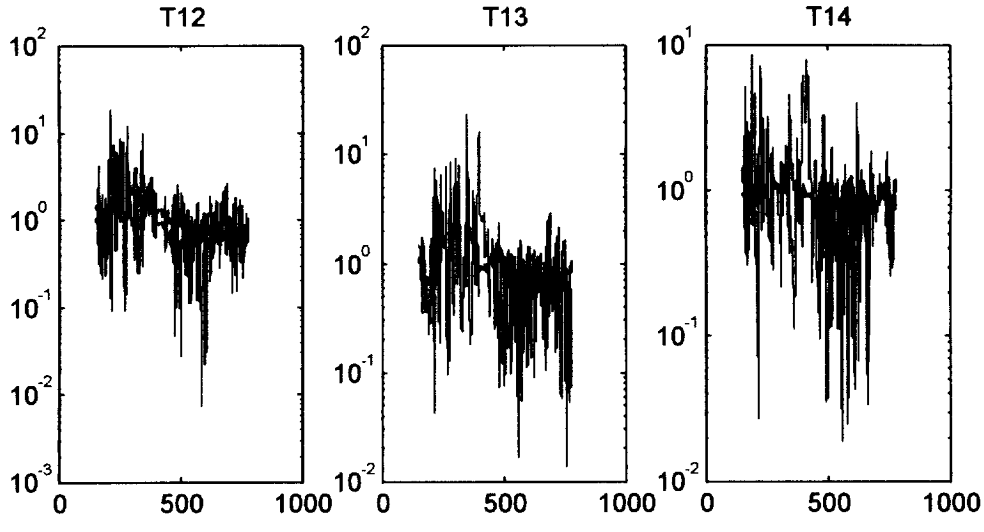

Figure 10. Three TFs for healthy1 and damage1 case for curved panel

Table 3. Summary of damage detection results for a curved panel

CASE	DAMAGE	DAMAGE INDICATOR (PIEZO-ACTUATOR, 152-780 HZ, 20 AVGS.)
Healthy 1	None	0.1938
Healthy 2	None	0.1809
Healthy 3	None	0.1670
Damage 1	100 kg mass top	1.2692
Damage 2	100 kg mass bot.	1.3360
Damage (cut)	2 in. cut from top	0.5313

This experiment also successfully detected damage, but again the number of frequency lines and number of averages can be increased to increase the sensitivity of the technique.

4.3 Damage Detection in a Composite Beam

A 3 inch by ¼ inch by 42 inch cantilever fiberglass beam is used to study damage detection on flexible cantilevered structures such as an aircraft wing or helicopter rotor. The test beam is shown in Figure 11. The damage simulated is: (a) added mass; and (b) saw cut (1/4 inch or 17% damage) top and bottom through the height of the beam. Sample TFs for the saw cut damage are shown in Figure 12 for the frequency range 0-600 Hz, and in Figure 13 for the frequency range 600-1200 Hz. The results of the damage detection study are listed in Table 4. The results of this damage study show that the very flexible beam which has a fundamental natural frequency of about 4 Hz. is not as repeatable as the plates tested which were stiffer. Also, since the damage detection prediction for the saw cut was within the noise level for the high frequency test, more frequency lines, more averages, and random excitation such as from a PZT patch should be used to improve accuracy.

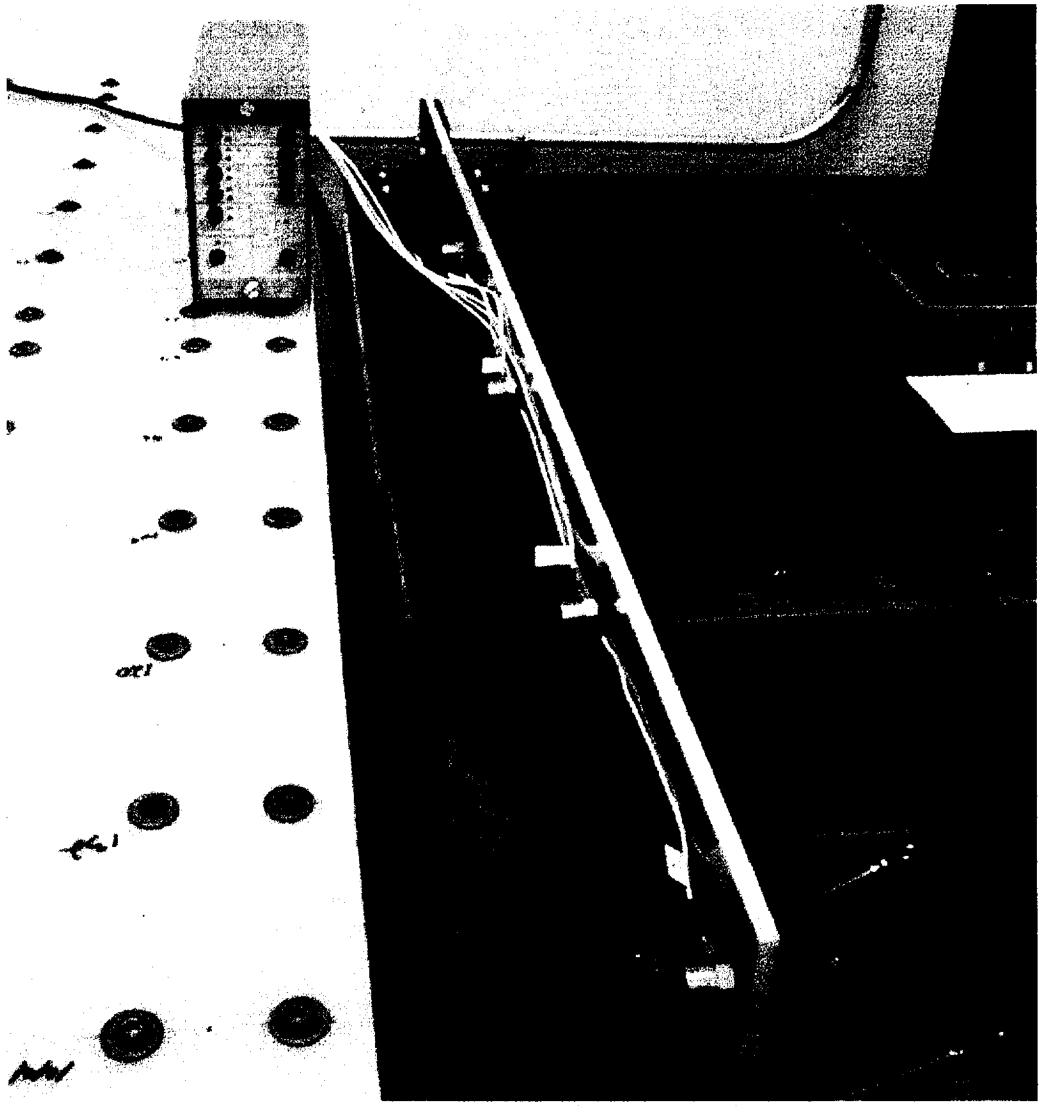

Figure 11. Fiberglass beam for damage detection

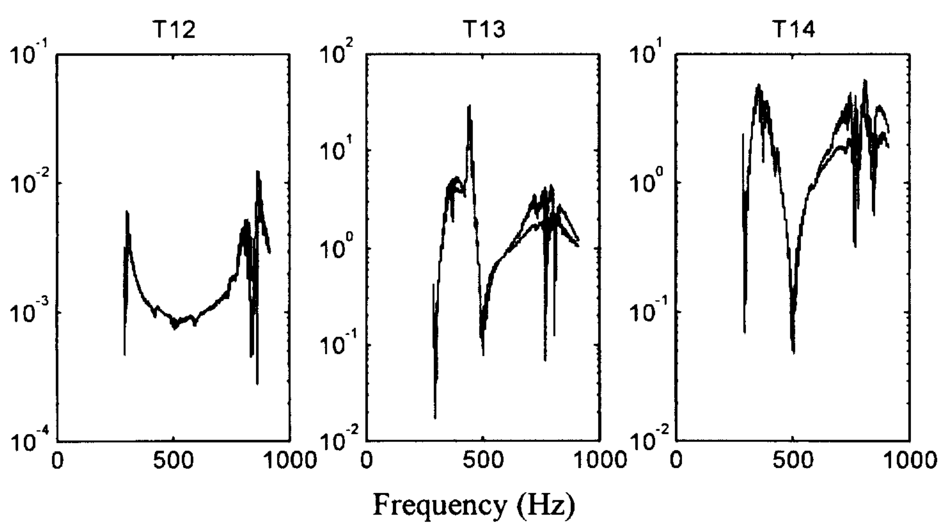

Figure 12. Three TFs for healthy1 and damage 5a case for a composite beam

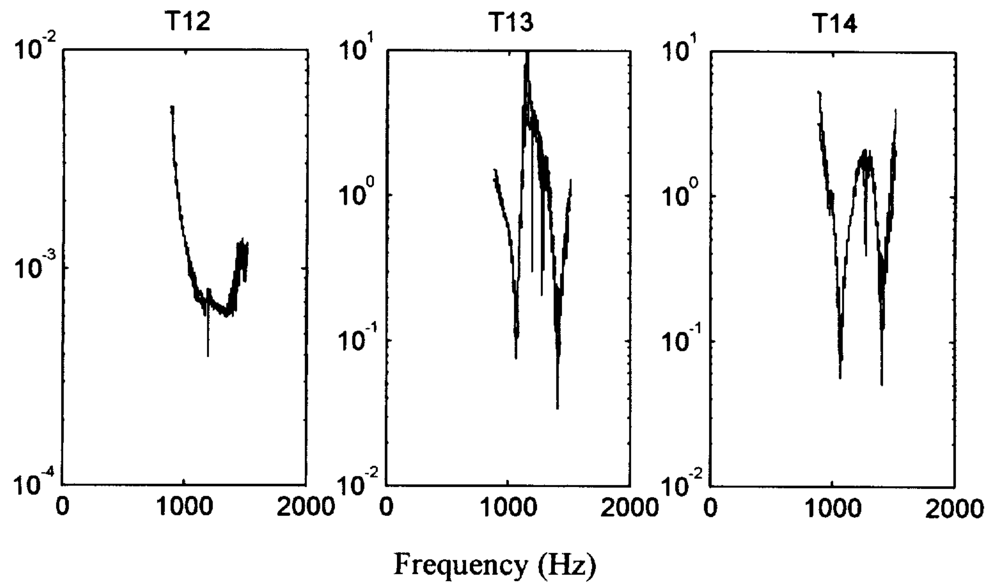

Figure 13. Three TFs for healthy1 and damage 5b case for a composite beam

Table 4. Summary of damage detection results for composite beam

Case	Damage	**Damage indicator** (Hammer excitation, 20 avgs.)
		(300-900 Hz)
Healthy 1	None	0.3851
Healthy 2	None	0.2954
Healthy 3	None	0.3111
Damage 1a, added mass	Element 1	1.4188
Damage 2a, added mass	Element 2	0.7700
Damage 3a, added mass	Element 3	1.0963
Damage 4a, added mass	Element 4	1.0970
Damage 5a, saw cut, ¼ in	Element 3 (17%)	0.5311
		(900-1500 Hz)
Healthy 1	None	0.3770
Healthy 2	None	0.4708
Healthy 3	None	0.3648
Damage 1b, added mass	Element 1	1.6770
Damage 2b, added mass	Element 2	0.9894
Damage 3b, added mass	Element 3	1.1169
Damage 4b, added mass	Element 4	1.1141
Damage 5b, saw cut, ¼ in	Element 3 (17%)	0.3970

The overall summary of these initial studies is that damage was detected on a flat plate, beam, and curved panel in a laboratory environment. Testing needs to be performed over the long term and on actual aerospace structures to further verify the technique. Also, more than four accelerometers or else a SLDV are needed to locate the damage. The noise level or non-repeatability should be improved by using random excitation/more averages and more frequency lines. Potential advantages of TFM method are that no structural model is needed, the excitation does not need to be measured, the diagnostic procedure is repeatable because environmentally induced changes are partly canceled by the ratio of response quantities in the TF, and the TFM technique is simple and suitable for autonomous damage detection.

5. REFERENCES

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6. Naser, A.S., Schulz, M.J., Pai, P.F., Thyagarajan, S.K., and Zhang, H., *"Self-Diagnostic Actively Controlled Structures,"* 11th VPI Symposium on Structural Dynamics and Control, May 12-14, Blacksburg, VA, 1997.

6. STUDENT AND FACULTY PARTICIPATION

The time spent on the project by the faculty members and students for the first year is listed below. All students working on the project are from underrepresented groups.

- The PI received two months release time to direct the project and develop the damage detection theories.
- The post-doctoral research associate worked four months on the project and worked with the students and set-up the experimentation on the project.
- The adjunct faculty member and a technician worked on the project two weeks each to help set-up the composite materials and fixtures and to evaluate the testing.
- One graduate student is working full time over the summer on the project and will work part-time during the semesters.
- A second graduate student worked part time on the project to set-up the fixturing during the spring 97 semester. This student stopped working on the project.
- An undergraduate student worked the spring 97 semester and built the frames for the test fixtures. He will also work the fall 97 semester and beyond.
- A second graduate student will be hired the fall 97 semester.
- A high school senior worked on the project for six weeks in the summer. She helped the graduate student perform testing and reduce data from the experiments. She was supported by the NASA SHARP Plus program, and not from this grant.

Although one student stopped working on the project after one semester, the other students built fixturing and learned to use the instrumentation, and have obtained good initial results that have been presented at the ICCE/4 conference, July 6-12, 1997.

7. PRESENTATIONS AND CONTACTS

The following presentations have been made thus far in the project, some of the results presented involve leveraged support from different projects that the PI has on health monitoring.

a) Conference Proceedings
   - Presentations at three conferences were made on health monitoring techniques in which the research was partly supported by this project. These papers are listed as references 4-6 in this report.

b) Technical Society Presentation
   - The undergraduate student made a presentation on the fixturing and testing he performed to the American Society of Mechanical Engineers (ASME) meeting in Greensboro, NC, April 17, 1997.

c) Contact with technical monitor
   - The PI and technical monitor have regular phone contact on progress of the project. The PI has sent the technical monitor the papers published, a 65 page viewgraph summary of the project results, and this project report. The technical monitor is also sending material to the high-school student and corresponded with her by e-mail for background on her project on health monitoring.

d) Other Contacts
   - The PI is going to share results with Professor Manfred Hertwig of the Netherlands on applying laser technology for health monitoring.

8. CONTINUING RESEARCH

Specific aspects of the health monitoring technique that need improvement will be investigated during the second year of the project. These are listed as: improve the damage locator algorithm; test curvature, multi-point, and higher-order TF algorithms; develop a version of the algorithm without using historical data; induce environmental changes and test the damage algorithms; use PZT patches for sensors and actuators; use a Scanning Laser Doppler Vibrometer and a fixed reference laser to get dense spatial measurements to locate damage; and this project must also test the technique on full size structures. A test on a tail section of an aircraft is planned first, and then testing on an out-of-service airplane. These are aluminum structures but can be used to verify the technique as large composite structures are not available for testing. The results from testing the aluminum structures will prove the general applicability of the technique, extension to composite materials is being verified through the testing that is being performed on the 4 ft fiberglass panels, and other graphite-epoxy panels. We plan to give a demonstration of the technique to the technical monitor by the end of the second year of the project.